

# Advances in measurements of ultrasound fields in the frequency range 20–60 MHz

E. G. Radulescu, P. A. Lewin and A. Nowicki

**Abstract**— A powerful measurement technique suitable for virtually continuous calibration of ultrasonic hydrophone probes in the frequency range 250 kHz – 60 MHz is described and frequency responses of PVDF polymer hydrophones are presented. The validity of the calibration results was examined using independent calibration techniques. The values of sensitivity in  $V/Pa$  obtained using a linear swept frequency technique were compared with those which were determined from the measurements employing nonlinear wave propagation. Also, the sensitivity against frequency data obtained here were compared with the data provided by an independent national laboratory. The overall agreement between the calibration results obtained using different techniques mentioned above was within  $\pm 1$  dB at the frequencies up to 25 MHz. The uncertainty increased gradually with increasing frequency and was determined to be  $\pm 2.5$  dB at 60 MHz. Spatial averaging correction model is being developed to minimize this uncertainty. The near continuous frequency plots in the 40–60 MHz bandwidth were not reported so far and reveal that the ultrasonic hydrophone probes response is largely controlled by their design architecture.

## I. INTRODUCTION

DIAGNOSTIC ultrasound is used in almost all medical fields and is quickly becoming the preferred imaging modality in a variety of clinical situations. Ultrasound image quality upon which the final diagnosis critically depends has improved significantly in the past decade and this would not have been possible without several engineering and technological innovations and breakthroughs. One of these major innovations is associated with the advent of superwideband, sensitive, multielement imaging transducers. While in the past decade a majority of those transducers operated at the fundamental frequencies in the vicinity of 5 MHz, in the recent years the clinical examinations are often carried out at harmonic frequencies often exceeding 10 MHz. Harmonic images have already proved to be capable of providing a degree of detail which clearly surpasses that available with conventional, fundamental frequency gray scale imaging. Consequently, within the next half decade it may be expected that harmonic imaging capability will become a standard available in a new generation of ultrasound imaging equipment and will be widely used in all clinical ultrasound applications. Also, the interest in the visualization of tissues at frequencies beyond 20 MHz is gaining attention because the higher imaging frequencies are capable of providing sub-millimeter resolution, highly desirable, for instance, in studying skin dis-

eases. One of the important aspects of this development in ultrasound imaging is that it created a need for calibrated hydrophone probes suitable to perform quantitative measurements of acoustic fields at these high frequencies. However, the commercially available probes are typically calibrated in the frequency range 1–15 or 20 MHz. Although this paper focuses on the development of the measurement techniques applicable beyond 20 MHz, the results presented also include the hydrophone responses below 1 MHz. This is because this response is important in determining the Mechanical Index, which is widely accepted as an indicator of potential bioeffects [1]. In the following, the measurement techniques developed to calibrate hydrophone probes in the frequency range from 250 kHz – 60 MHz are briefly described and the (nearly continuous) frequency responses of different probes are presented and examined to determine the overall uncertainty of the calibration. Finally, the methods to minimize the overall uncertainty of the measurements are pointed out.

## II. MEASUREMENT ARRANGEMENT

In Fig. 1 the experimental set up used here is shown. The wideband approach used here to obtain the majority of calibration data was based on swept frequency measurement technique. The details of this technique can be found in [2]. Briefly, the technique, often referred to as Time Delay Spectrometry, allows free-field acoustic measurements to be carried out in a reflective environment.

The description of the wideband focused PVDF source used to produce the signals in the frequency range 1–60 MHz is given in [3]. The design of the composite PZT transducer employed in the low frequency calibration can be found in [4].

Fig. 1 set up was also utilized to perform calibration using nonlinear approach [5] in which a circular, 5 MHz highly focused source with focal number 5.2 was used to produce fundamental and harmonics in the frequency range 5–60 MHz.

## III. RESULTS

In Fig. 2 the frequency response of the coplanar Marconi membrane hydrophone is shown in the frequency range from 250 kHz – 60 MHz. To maximize signal-to-noise ratio, the output signal from the hydrophone was routed via custom-built, wideband, 20 dB preamplifier. The solid plot represents the data obtained using the swept frequency technique described above and the open circles represent the discrete calibration points in the frequency range 2–50 MHz supplied by a national laboratory (NPL, UK). This

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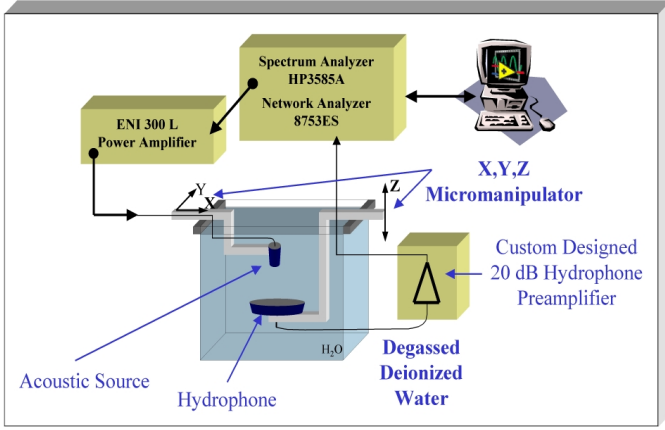


Fig. 1. Measurement arrangement for the (linear) swept frequency calibration

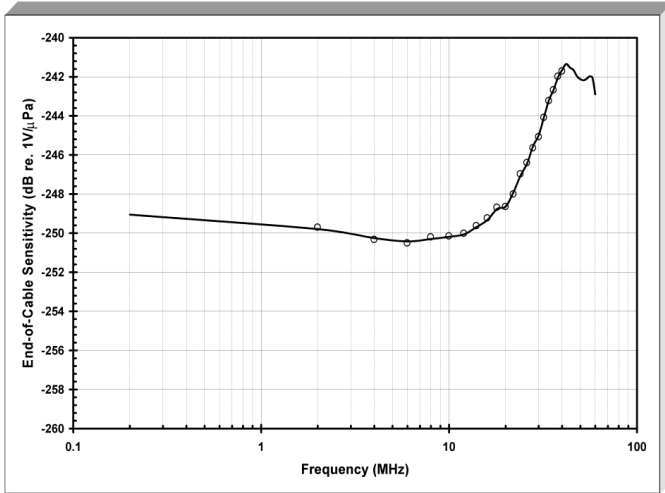


Fig. 2. Frequency response of a 0.5 mm diameter coplanar PVDF membrane hydrophone (Marconi, UK). Solid line: swept frequency calibration, open circles: National Physical Laboratory (UK) data. End-of-cable sensitivity level was amplified (20 dB) to maximize the signal-to-noise ratio.

coplanar hydrophone was used as a reference hydrophone in the calibration of another (shielded, bilaminar) membrane hydrophone (Sonic Technologies, now Sonora Medical Systems, Colorado, USA) and the results of this calibration are shown in Fig. 3. Similarly, the calibration was performed in the frequency range from 250 kHz to 60 MHz. Again, the solid line represents the data obtained using the swept frequency technique. The solid circles represent discrete frequency calibration data obtained using nonlinear KZK approach [5]. Since the effective finite apertures of the reference and bilaminar hydrophone probe differed slightly the data shown were corrected using the spatial averaging correction model [6].

#### IV. DISCUSSION AND CONCLUSIONS

The results presented in Fig. 3 indicate that the calibration data obtained in this work and the ones provided by an independent laboratory are in very good agreement. The

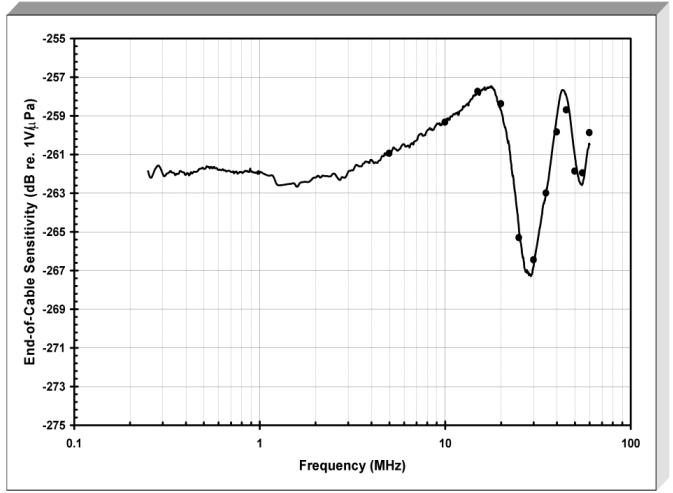


Fig. 3. Frequency response of a 0.5 mm diameter shielded, bilaminar Sonic Technologies (now Sonora Medical Systems) PVDF membrane hydrophone in the frequency range 250 kHz – 60 MHz. Solid line: swept frequency calibration, solid circles: nonlinear KZK data.

overall uncertainty of the measurements reported here has increased with increasing frequency from approximately  $\pm 1$  dB at 25 MHz to about  $\pm 2.5$  dB at 60 MHz. To minimize this latter value, the applicability of the spatial averaging model described in [6] is being extended to 60 MHz. The application of the model has already lessened the overall uncertainty at 40 MHz to approximately  $\pm 1.5$  dB and it is expected that once the model is verified at the frequencies beyond 40 MHz, the  $\pm 2.5$  dB uncertainty will be reduced.

The results shown in Fig. 3 reveal several interesting details of the bilaminar hydrophone behavior at the frequencies beyond 40 MHz and to the best of the authors' knowledge such data were not reported so far. Similar hydrophones were calibrated in the frequency range 1–100 MHz [5] using discrete nonlinear approach and the results presented in [5] confirm that the bilaminar construction of the hydrophones leads to peaks and valleys in their responses against the frequency. The resonance observed in Fig. 3 in the vicinity of 18 MHz is associated with the fundamental frequency of approximately  $50 \mu\text{m}$  thick two layer PVDF structure [7]. The existence of the 28 and 55 MHz minima and the 43 MHz resonance (see Fig. 3) was also corroborated by the results presented in [5], however, the source or origin of the variation in the sensitivity beyond 20 MHz is less obvious. Determination of this source would require a more detailed knowledge of the thickness of the glue layer between the two PVDF films [7] and then a careful simulation of, in practice, three layer construction using piezoelectric transducer modeling tool such as PIEZOCAD (Sonic Concepts, Woodinville, WA, USA). The response of the bilaminar hydrophone probe below 1 MHz is in excellent agreement with the results presented in [4] and [8] and shows that well below the fundamental resonance the hydrophone sensitivity is essentially flat.

In conclusion, a powerful measurement technique allowing virtually continuous calibration of the PVDF probes

in the very wide frequency range from 250 kHz – 60 MHz was developed and verified. Current work is concentrated on extending the swept frequency calibration method up to 100 MHz and minimizing the overall uncertainty. As already noted, this work will require further refinement of the spatial averaging correction model [6] and availability of the very high frequency, wideband acoustic sources. Similarly, further reduction of the lower limiting frequency of 250 kHz will require availability of a high efficiency acoustic source capable of generating output signals in the frequency range from, say, 100 kHz to 2 MHz. The upper frequency of 2 MHz is needed to ensure the continuous frequency overlap with the 1 MHz - 60 MHz sources used here. The implementation of such low frequency source represents quite a challenge as it would need to be designed for the fundamental resonance frequency of approximately 2 MHz, however, below the resonance, the transmitting voltage response decreases at approximately 12 dB per octave and, therefore, may lead to inadequate signal to noise ratio during measurements performed below 200 kHz.

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